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Building the hydrogen economy in China: Drivers, resources and technologies

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ABSTRACT

This paper reviews drivers, resources, and technologies for building the hydrogen economy in China. China is unique in terms of its vast area, huge population and fast economic growth. These factors pose a great challenge for China to ensure a continuous and sufficient energy supply. In addition, the coal-based energy system of China inevitably results in huge CO_2 emissions. Hydrogen shows the great potential in solving the concerns for improving energy security and reducing greenhouse gas emissions. Hydrogen can be produced from abundant and widely distributed renewable energy resources, which implies an opportunity for China to diversify its energy supplies from a hydrogen economy. Moreover, hydrogen is the cleanest fuel especially when coupled with fuel cell. Chinese government has made ambitious policy and provides strong financial support for research and development of hydrogen and fuel cell technology. All the top-tier universities and institutes in China are conducting related research and Chinese companies express strong interest in the commercialization of hydrogen and fuel cell technology.

Contents

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1. Introduction

The major concern for improving energy security and reducing greenhouse gas emissions, together with the rapid development of hydrogen and fuel cell technology in recent years, is focusing Chinese opinions on options for future hydrogen economy. The burgeoning need for energy coupled with the rapid depletion of fossil fuels poses serious threats to the energy security of China. This is especially true considering the fact that China has become the world's second-largest net importer of oil since 2009. In addition, the economy structure of China also has a major impact on its greenhouse gas emissions profile and its consequent approach to address climate change. Currently, China relies heavily upon coal-fired power for electricity generation and is the leading emitter of greenhouse gases (measured in absolute terms).

Hydrogen seems to be a promising candidate for solving the energy concerns of China. Hydrogen can be produced from a variety of sources, both fossil fuels (coal, oil, natural gas) and renewable resources (hydro, wind, solar, biomass). On the other hand, China has abundant coal reserves and renewable energy resources while oil and natural gas reserves are limited. This provides an opportunity for China to diversify its energy supplies from a hydrogen economy. Hydrogen can then be utilized in high-efficiency power generation systems, including fuel cells, for both vehicular transportation and distributed electricity generation. Overall, emissions in a hydrogen energy cycle are expected to be lower than today's carbon energy cycle, but the centralized production of hydrogen offers the extra advantage of enabling large scale capture and sequestration of CO_2 emissions. Sequestration, along with the efficiency improvement due to fuel cell technology, could make a major difference in emissions from a hydrogen economy.

In this work, we reviewed key issues concerning the transition of China towards hydrogen economy. First, a brief introduction to its geographic and economic data, together with its energy consumption profile, is presented. Then, the drivers of building hydrogen economy in China are discussed. A section on energy supply and potential sources for hydrogen production follows. Finally, the interests in hydrogen and fuel cell technology within China are reviewed.

2. Geography, economy and energy consumption

China is the world's second-largest country by land area, covering 9.6 million square kilometers; it also has the highest population in the world, with more than 1.3 billion citizens [1]. However, the population distribution of China conceals major regional variation. Most of the population is concentrated in the eastern part of China, especially the coastal region. These areas also tend to be more industrialized. In contrast, the west and northern part of the country are very sparsely populated and less developed. Fig. 1 illustrates the distribution of population and major cities in China [2].

Since the initiation of its economic reforms in 1978, China has become one of the world's fastest-growing economies, with annual growth rates averaging 10% over the past 30 years. China became the world's second largest economy after the United States in 2010 [3]. It was reported by the National Bureau of Statistics

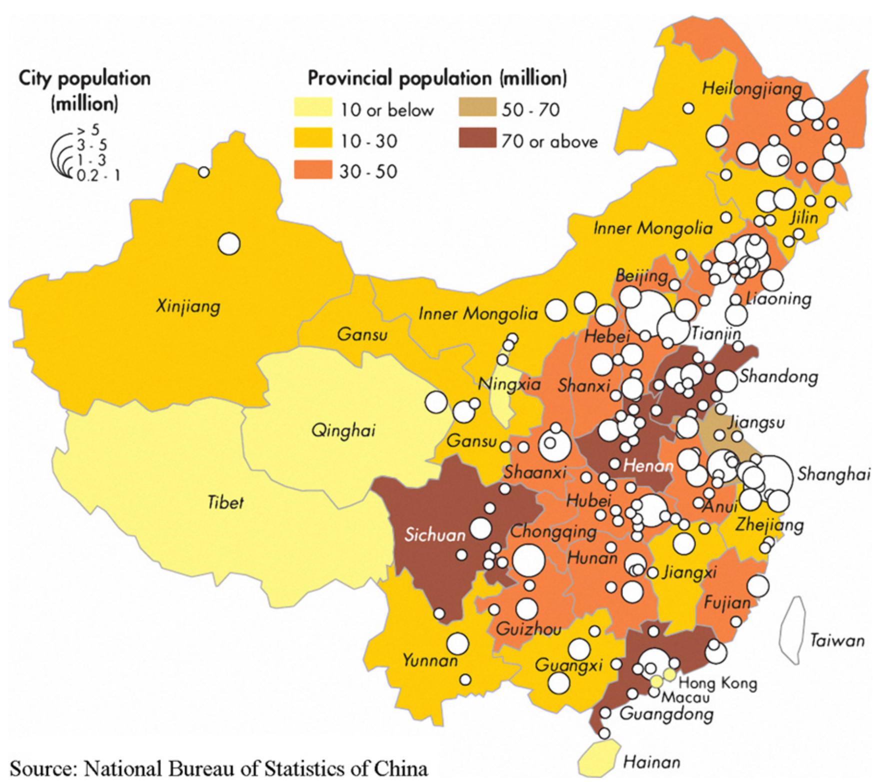


Fig. 1. Distribution of population and major cities in China [2].

that the GDP of China reached $7.26 trillion in 2011 [4]. Meanwhile, China is also the largest exporter and second largest importer of goods in the world. According to the data released by the General Administration of Customs, the total foreign trade volume of China totaled $3.64 trillion in 2011 [5].

The energy consumption of China is soaring as its economy is expanding rapidly. China overtook the United States and became the world's largest energy user in 2010 [6]. Currently, China accounts for 21.3% of the world's energy demand but its rate of consumption is growing more than four times the world's rate [7].

Fig. 2 shows the energy consumption of China by fuel in 2000 and 2010 [7]. As can be seen, coal is the backbone of the country's energy system. It meets over half of its primary energy needs, providing most of the fuel used by power stations and much of the final energy used by industry, commercial businesses and households. In fact, coal's importance in the overall energy mix has been growing in recent years, due to the booming demand for electricity, which is almost 80% coal-based. Oil demand has been growing quickly, with total oil consumption increasing from 230.1 million ton oil equivalent (toe) in 2000 to 437.7 million toe in 2010. However, its share of primary demand decreases from 28.6% to 18.2%, reflecting the huge increase in the total energy consumption during this period. While China has made an effort to diversify its energy supplies, hydroelectric sources, natural gas, nuclear power, and other renewables account for relatively small shares of the country's energy mix.

Fig. 3 shows the energy consumption of China by sector in 2009 [8]. In 2009, the industrial sector—including manufacturing, utilities, and mining—is the country's largest energy user, accounting for 72% of total energy use. The residential sector is next with about 11%, while transport, storage and post also contribute almost 8%. The agriculture, forestry, animal husbandry, fisheries, and water conservation sectors together only account for about 2%, reflecting the low level of agricultural mechanization in China.

3. Drivers of building the hydrogen economy in China

In a recent literature overview of hydrogen studies, four main drivers towards hydrogen economy were identified: (1) energy security, (2) climate change, (3) air pollution and (4) competitiveness [9].

3.1. Energy security

China did not realize the urgency and importance of energy security until the 1990s due to the weak economic development and relatively lower demand for energy resources before 1990s. For many years, China was able to meet its energy needs entirely from domestic resources. Therefore, energy security was not the country's priority as its dependence on global markets was minimal.

However, the situation has changed dramatically in the last decade and concerns about energy security have grown in parallel. The energy consumption of China has been soaring due to the rapid economic growth, expanding middle class population and the largest-scale of urbanization. China was forced to end its self-sufficient oil policy and import oil from overseas in 1993. In 2009, China became the world's second largest consumer of oil behind the United States and the world's second largest net importer of oil [10]. In less than a generation, China has moved from being a minor and largely self-sufficient energy consumer to one of the world's fastest-growing energy consumers and largest energy importers.

Energy security considerations of China today focus largely on guaranteeing a continuous and sufficient supply of oil from overseas. Currently, China depends on foreign imports for over 50% of the oil it consumes, and half of this imported oil is from the Middle East [11]. Fig. 4 shows the country's crude oil imports by source in 2010 [10]. China has many reasons to worry about its oil supply: small oil reserves, high dependence on oil imports, dramatic fluctuation of oil prices in international market, and political risk in oil-supplying countries.

On the other hand, China has abundant and widely distributed renewable energy resources that have the potential to gradually displace fossil fuel in the country's energy mix. It is more desirable for China to draw its energy to a large extent from local and indigenous renewable energy resources, with much less dependence on energy imports from overseas. The use of hydrogen can facilitate the exploitation of the renewable energy resources. Hydrogen can be produced from diverse resources, both renewable (solar, wind, hydro, biomass) and non-renewable (coal, oil, natural

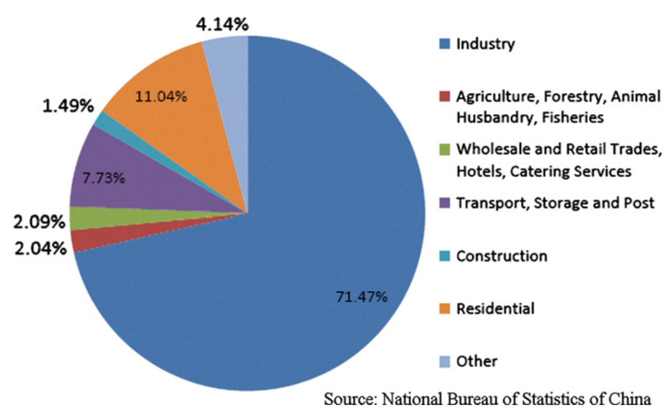


Fig. 3. Energy consumption of China by sector in 2009.

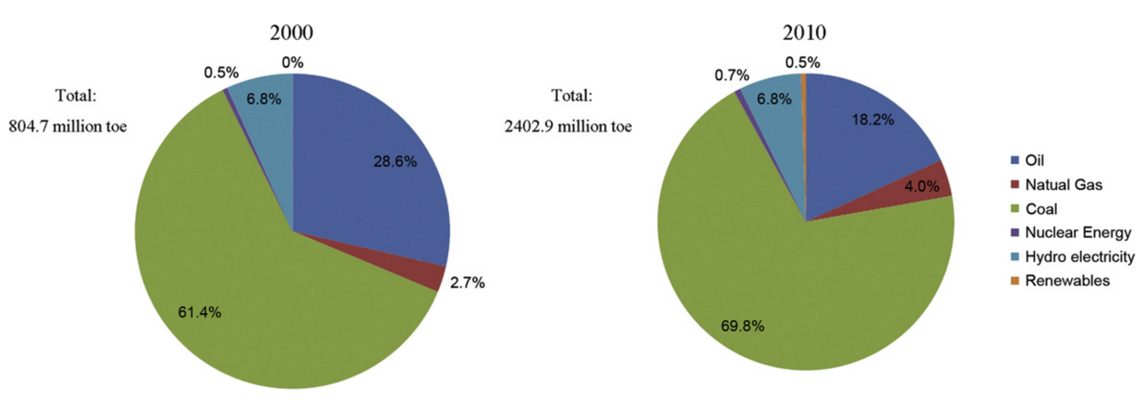


Fig. 2. Energy consumption of China by fuel in 2000 and 2010.

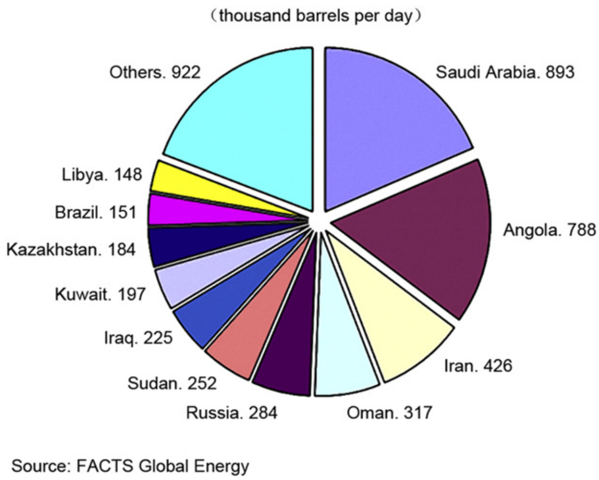


Fig. 4. Crude oil imports of China by source in 2010

gas) [12]. It is important to stress that, unlike coal, oil or natural gas, hydrogen is not a primary energy source. Its role more closely reflects that of electricity as an "energy carrier", which is produced using energy from another source and then transported for future use, where its stored chemical energy can be utilized. It is the key element of the energy storage capacity that provides a solution to one of the major issues of renewable energy resources, namely the vexing problem of intermittency of supply. For instance, many people have predicted the growth of a solar/wind hydrogen economy in the future. Photovoltaic panels or wind turbines would convert sunlight or wind into electricity. The electricity would be used to split water (electrolysis) into hydrogen and oxygen so as to store energy as hydrogen fuel. Fuel cells then consume the hydrogen to generate stable electrical power [13].

In sum, hydrogen opens up the possibility of (decentralized) production and utilization on the basis of a variety of energy sources, thus diversifying energy supply. This may greatly contribute to reduce the dependence on imported oil [14].

3.2. Climate change

Emissions of carbon dioxide (CO_2), the main greenhouse gas (GHG) from human activities, are the subject of a worldwide debate about energy sustainability and the stability of global climate. Due to heavy industry background and fast growing economy, CO_2 emissions in China tripled between 1990 and 2009, reaching almost 7 billion tons (Gt) of CO_2 in 2009 (24% of global emissions). In fact, China overtook the United States in 2007 as the world's largest annual emitter of energy-related CO_2 [15].

China plays a critical role in the battle against world climate change caused by the greenhouse gas emissions. The Kyoto Protocol of December 1997 represents the first international common action towards GHG emission controls. As one of the major stakeholders of the Kyoto Protocol, China promised in 2009 that China was going to reduce the intensity of carbon dioxide emissions per unit of GDP in 2020 by 40%–45% compared with the level of 2005.

Reduction of GHG emissions requires substantial modification in conversion and utilization of different energy sources, including [16]

- efficiency improvement, with reduction of fossil fuel consumption;
- use of low-carbon or carbon-free energy sources;
- separation and sequestration of the CO_2 produced from fossil fuels.

Hydrogen has a variety of good properties and perfectly matches these requirements. If hydrogen is produced from renewable energy resources (e.g. wind or solar), it is a genuine emission-free-fuel. Even if fossil fuels (e.g. coal) are used as feedstock, large-scale production of hydrogen provides additional opportunity of CO_2 sequestration, which involves the capture and storage of huge quantities of CO_2 underground (e.g. in depleted natural gas and oil wells or geological formations). When coupled with fuel cells, hydrogen can achieve the best efficiency of over 50%, which is much higher than that of conventional internal combustion engines. Actually, the development of technologies for distribution and utilization of hydrogen will be the basis for the introduction of those CO_2-free energy technologies [16].

3.3. Urban air pollution

China is facing serious urban air pollution problem. It is now home to 13 of the world's 20 most polluted cities [17]. The vehicle exhaust emissions have been blamed for the main contributor to the worsening air quality in big cities. Since 2009, China has been the largest automobile market in the world. Its annual vehicle production and sales reached 18.26 million and 18.06 million in 2010. By the end of 2010, the vehicle population in China has totaled 190 million. It was reported by the Ministry of Environmental Protection that the total volume of vehicle exhaust emissions reached more than 52.26 million tons in 2010, including 40.80 million ton of carbon monoxide (CO), 4.87 million ton of hydrocarbon (HC), 5.99 million ton of nitrogen oxide (NO_x) and 598,000 t of particulate matter (PM) [18]. The Ministry of Environmental Protection uses air pollution index (API) to evaluate urban air quality. When API exceeds 100, it is defined as overproof pollution. If the days of overproof pollution are more than three days, it is defined as a process of chronic pollution. Fig. 5 shows the air quality of Beijing during 2001–2010 [19]. As can be seen, although the air quality keeps improving, Beijing still has to face overproof pollution in almost a quarter of one year.

Fuel cells are considered to be the most promising power source for future generation vehicles and the only technology with the potential of competing with internal combustion engines [16]. Fuel cell vehicles offer efficiencies two to three times higher than those of conventional vehicles, maintaining similar performances in terms of range, top speed and acceleration. Moreover, by skipping the combustion process that occurs in traditional internal combustion engines, the generation of pollutants during the combustion process is avoided. With pure hydrogen, a fuel cell vehicle is a true "zero emission" vehicle, producing only water as by-product. Even with other fuels, emissions from fuel cell vehicles will be very low with near-zero levels of NO_x, SO_x and particulates, therefore eliminates 20,000 kg of acid rain and smog-causing pollutants from the environment. In any case fuel cells generally provide the lowest emissions of any non-renewable power generation method, as shown in Table 1 [20].

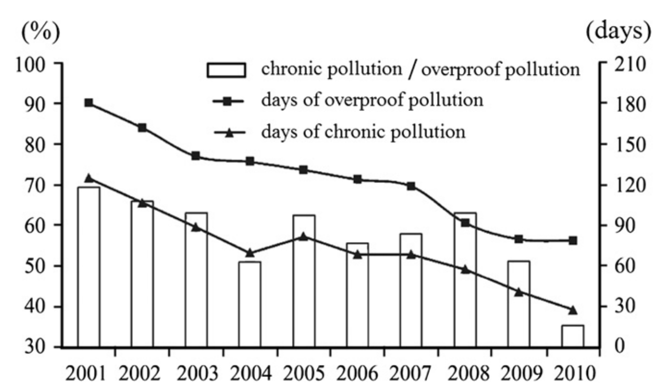


Fig. 5. Air quality of Beijing during 2001–2010 [19].

3.4. Competitiveness

The global competitiveness of China will be fostered if Chinese companies are able to forge a lead in hydrogen and fuel cell technology. The country's automobile industry would be a good example to illustrate this point. China is currently the largest automobile market in the world. Although some indigenous automobile manufacturers are emerging, foreign companies still occupy the largest market share and take a leading position in many key technologies, especially the internal combustion engine [21]. As such, indigenous automobile manufacturers can hardly compete with their foreign counterparts in the domestic market, let alone the global market. The emergence of fuel cell provides an opportunity for Chinese companies to reverse the tide. They intend to develop fuel cell vehicles to leapfrog internal combustion engine vehicles [22]. Using this strategy, the indigenous manufacturers are able to stand on the same starting line with their foreign counterparts for the first time.

4. Energy resources for hydrogen production in China

The reserves of fossil fuels in China show imbalanced. China has the world's third-largest coal reserves while its oil and natural gas reserves are relatively limited compared to its consumption. As a result, China has become a net importer of oil and natural gas. In addition, the distribution of these resources conceals major regional variation: the majority of coal and oil reserves are in the north while the majority of natural gas reserves are in the west and central. This implies location mismatch between major energy suppliers and major energy consuming cities, most of which lie in the eastern part of China, especially the coastal region. On the other hand, renewable energy resources (hydro, wind, solar, biomass) are abundant and widely distributed across the country. However, most renewable energy resources remain unexploited.

China is the world's largest hydrogen consumer with 22% of global hydrogen consumption share [23]. The maximum demand in China comes from ammonia producers. On the other hand, fossil fuels play a dominant role in the country's hydrogen production, accounting for 97% of total hydrogen production. Water electrolysis only contributes to 3% of total hydrogen production [24]. Considering the vast unexploited renewable energy resources, China is eager to produce hydrogen from them in the future.

Table 1
Pollutant emission factors for the total portion of the fuel cycle [20].

Source	SO_x (gSO_x/kWh)	NO_x (gNO_x/kWh)	C in CO_2 (gC/kWh)	C in CO (gC/kWh)	Particles
Coal	3.400	1.8	322.8	40.0	0.00020
Oil	1.700	0.88	258.5	40.0	0.00015
Natural gas	0.001	0.9	178.0	20.0	0.00002
Nuclear	0.030	0.003	7.8	7.8	0.00005
Photovoltaic	0.020	0.007	5.3	1.3	0
Fuel cells	0	0	1.3	0.3	0

4.1. Coal

China held the third-largest coal reserves in the world behind the United States and Russia [10]. In 2003, the Ministry of Land and Resources of China, in accordance with international norms for coal resources reporting [25], stated that the country's total coal reserves stood at 1021 Gt, comprising 334 Gt of "basic reserves" and 687 Gt of "prognostic reserves" [26]. "Proven reserves" were reported to be 189 Gt, suggesting a reserve-to-production ratio of over 70 years. According to the norm [25], "basic reserves" are defined as those resources that can be potentially exploited under current technoeconomic conditions. "Prognostic reserves" include those amounts that are not economic to recover or for which economic significance is uncertain because data is insufficient. "Proven reserves" are the economically recoverable fraction of basic reserves.

The distribution of coal resources shows imbalanced, as shown in Fig. 6 [26]. Most resources are in the west and northern part of the coutnry. Shanxi, Shaanxi and Inner Mongolia together account for 65% of the nation's proven coal reserves, while just 13% lie in the southern region, mainly in Guizhou and Yunnan. Over 90% of

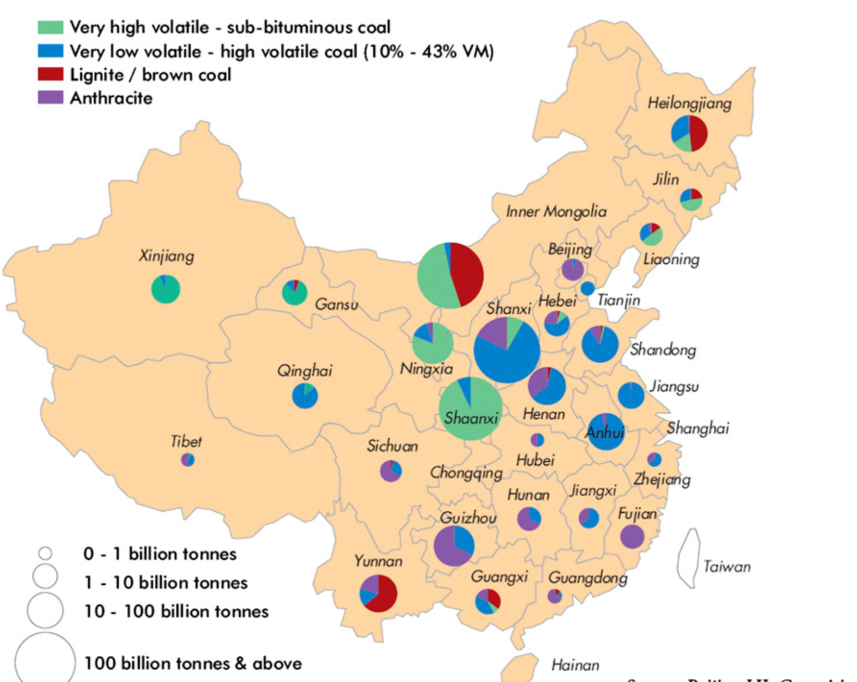


Fig. 6. Location of major coal resources in China [26].

identified coal reserves are in less-developed, arid areas that are environmentally vulnerable.

China is the largest producer and consumer of coal in the world [10]. Coal production rose to almost 3.1 Gt in 2009, making China overtake the United States to become the world's largest coal producer. Also in 2009, China consumed an estimated 3.2 Gt of coal, representing over 46% of the world total. Coal consumption has been on the rise in China over the last ten years due to the booming demand for electricity, which is almost 80% coal-based.

Gasification is the primary method for converting coal into hydrogen [27]. It is also the core of current Integrated Gasification Combined Cycle (IGCC) technology for power generation. In a commonly used gasification process, coal is first ground to a fine powder and mixed with water before being gasified at high pressure using pure oxygen. The feedstock is heated to high temperature (about 1400 °C), causing its decomposition and producing a mixture of hydrogen, carbon monoxide and some residues; the resultant synthesis gas stream is quenched and scrubbed. The syngas is then put through a CO shift reactor, and CO_2 is removed using a physical solvent. The acid gases contained in this solvent are desorbed by pressure reduction. The hydrogen can be further purified to remove any remaining impurities. In China, around 50 million tons coal is used for gasification each year [24].

4.2. Oil

According to *Oil & Gas Journal* (*OGJ*), China had 20.4 billion barrels of proven oil reserves as of January 2011 [10]. Fig. 7 delineates the location of some of the major Chinese oil basins [10]. As can be seen, the country's major oil fields are located in the northern region of the country. Particularly, the northwest's Xinjiang Province has received significant attention. Recently, China announced the plan to make Xinjiang into the country's largest oil production and storage base. It is also worth pointing out that about 15% of overall Chinese oil production is from offshore reserves, and most of its oil production growth likely will come from offshore fields.

China is the second largest consumer of oil and the second largest net importer of oil in the world [10]. In 2010, China produced an estimated 4.3 million barrels per day of oil and consumed an estimated 9.2 million barrels per day of oil, making the net oil imports reach about 4.8 million barrels per day [10].

Oil, especially low quality fuels such as petroleum coke or residuals might be used as a fuel for gasification (as with coal) to supply hydrogen [27]. Combined with desulfurisation and sequestration, oil-produced hydrogen could be made with almost zero emissions. In addition, light fractions of petroleum can be converted to hydrogen in much the same way as natural gas. The limitations of this process are that it is less efficient overall, and less hydrogen is produced due to the lower molar content of hydrogen in oil. In China, about 0.766 million tons of hydrogen is produced from oil each year [24].

4.3. Natural gas

Estimates of natural gas reserves in China vary dramatically depending on the source [28]. At the end of 2008, China National Petroleum Corporation (CNPC) announced that the country's total proven reserves amounted to 5.94 trillion cubic meters, including 3.09 trillion cubic meters of technically and economically recoverable reserves. However, other estimations are also available. In 2007, Cedigaz estimated that the country's proven reserves amounted to 3.7 trillion cubic meters, while the International Energy Agency (IEA) estimated that the country's recoverable, proven and probable reserves from identified fields amounted to around 5.0 trillion cubic meters. As with coal resources, the distribution of natural gas is uneven. The country's major gas fields are located inland, in the western and central parts of the country. Fig. 8 illustrates the major natural gas field and infrastructure in China [28].

The consumption of natural gas has been limited in China until recently. This was mainly due to the lack of infrastructure, particularly long-distance pipelines connecting inland gas fields to major consumer cities, mostly in the coastal region of China. Since the 1990s, the government has promoted the construction of

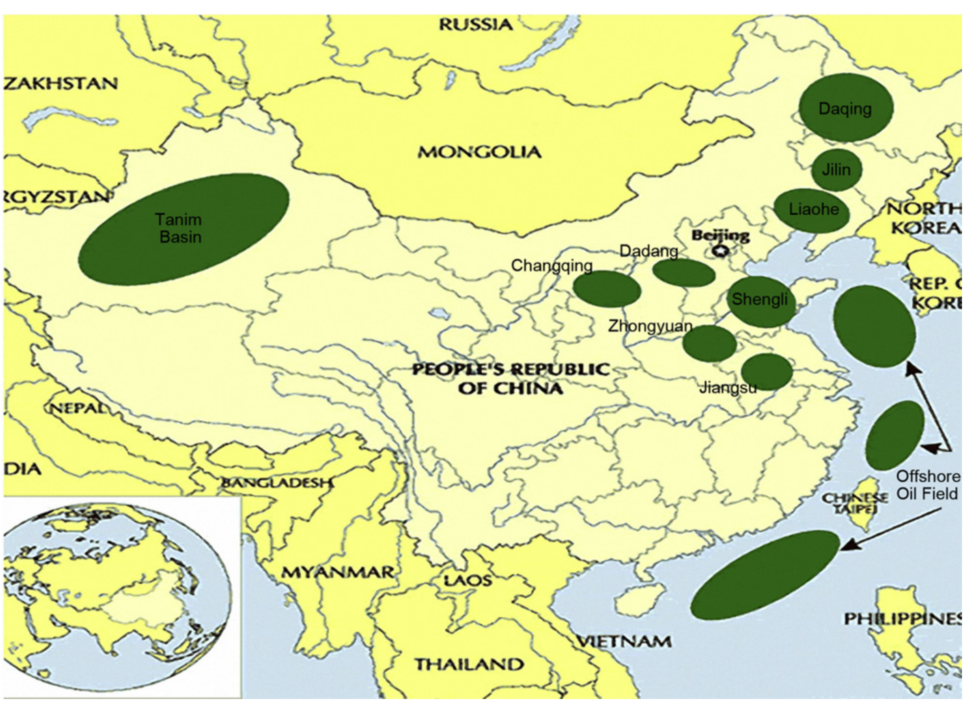
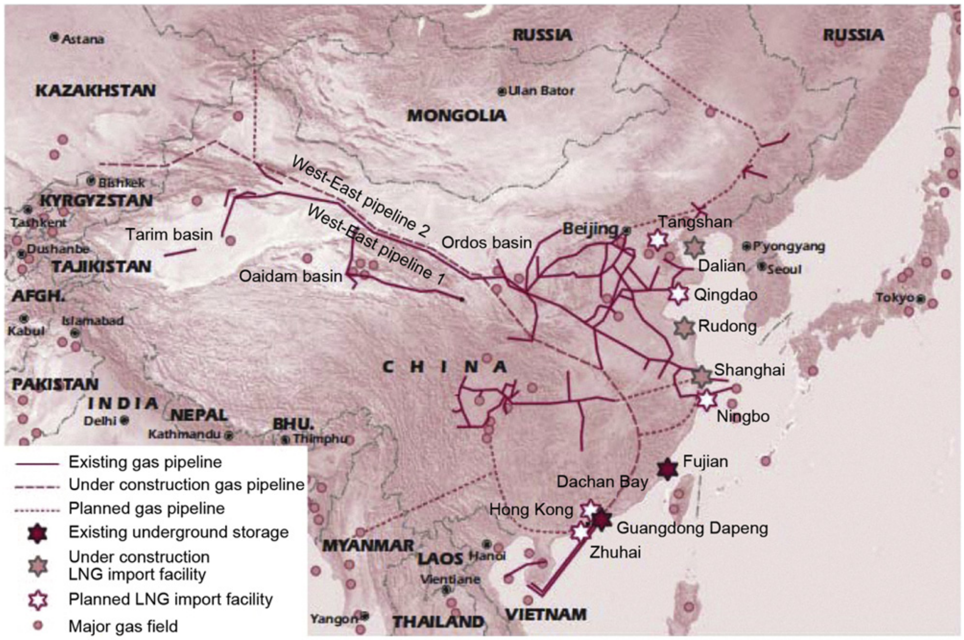


Fig. 7. Location of major oil resources in China [10].



Sources: China National Petroleum Corporation, Petroleum Economist, IEA

Fig. 8. Major natural gas field and infrastructure in China [28].

natural gas transport infrastructure and improved inter-regional connections between regional networks. The total length of natural gas pipeline across the country has amounted to 36,000 km by the end of 2010. China is ambitious to triple its current record to 100,000 km by the end of 2015 to meet the rising demand [29].

Although natural gas use is increasing in China, the fuel only comprises a small proportion of the country's total energy consumption. In 2007, natural gas production amounted to 69.2 billion cubic meters and consumption attained 69.5 billion cubic meters, making China a net natural gas importer for the first time in almost two decades [28]. Also in 2007, China became one of the world's top 10 countries in terms of natural gas consumption.

Hydrogen can be produced from natural gas directly via various processes, including steam reforming, partial oxidation, autothermal reforming and thermal decomposition, as well as indirectly via electrolysis using electricity and/or heat from gas combined cycle processes [27]. Nearly 60% of global hydrogen production is generated from natural gas. Hydrogen from natural gas for the ammonia and petroleum industries represents the largest portion of the current global production. In china, however, natural gas is mainly used as the feedstock for the production of chemicals due to its high price [30]. About 1.18 million tons of hydrogen is produced from natural gas in China each year [24].

4.4. Renewable energy resources

China boasts its fairly abundant renewable energy resources. These renewable energy resources offer the opportunity of zero fuel-cycle emissions for hydrogen production via electrolysis. According to the Medium and Long-Term Development Plan for Renewable Energy, China has a goal to generate at least 15% of total energy output by 2020 using renewable energy resources [31]. In recent years, China has strengthened its legislation to promote renewable energy, including the Atmospheric Pollution Prevention and Control Law 2000, the Renewable Energy Law 2005 and the Energy Conservation Law 2007. Meanwhile, China is the world's top investor in renewable energy projects, having invested around $120 billion to $160 billion between 2007 and 2010 [10].

4.4.1. Hydropower

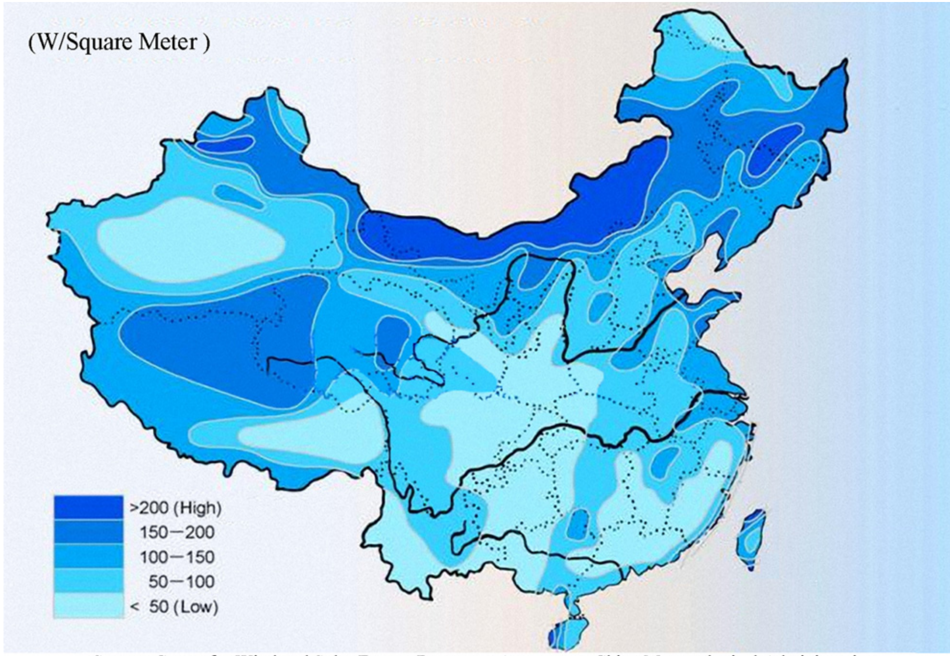
Hydropower is the most important renewable energy resource in China. According to the results of the 2003 Nationwide Hydropower Resource Assessment, the country's technically recoverable hydropower totals 542 GW, with an annual power generation potential of 2470 TWh. Its economically feasible hydropower resource is estimated to be 400 GW, with an annual generation potential of 1750 TWh, of which small-scale hydropower accounts for 125 GW, widely distributed across the country, especially in the southwest [32].

China was the world's largest producer of hydroelectric power in 2010, generating 721 TWh of electricity from hydroelectric sources, representing around 17% of domestic electricity use [33]. China also had the highest installed hydropower capacity, with 213 GW at the end of 2010, accounting for one fifth of the world's total installed hydropower capacity.

Small hydropower plays a key role in the electrification of China, especially in remote rural areas. Small hydropower generally refers to plants below 50 MW. About one-third of its remote towns rely on small-scale hydropower as their main source of electricity. With supportive policies and incentives, China had more than 55 GW of small-scale hydropower projects by the end of 2010, with a generating output of about 160 TWh [34].

4.4.2. Wind

Wind is the second leading renewable source for power generation in China. The country's recoverable onshore wind resources are 253 GW, ranking the first in the world, with a further offshore potential of 750 GW [35]. Fig. 9 shows the country's annual average wind power [35]. As can be seen, areas rich in wind resources are located mainly along the southeast coast and the northern region. In addition, the ocean-based wind resources are also abundant. With current technology, wind turbines can be installed in the ocean up to 10 km away from the coast and at the depth of up to 20 m.



Source: Center for Wind and Solar Energy Resources Assessment, China Meteorological Administration

Fig. 9. Annual average wind power in China.

Wind power is the most cost-effective renewable energy today. According to the data released by Greenpeace and the Chinese Renewable Energy Industries Association, China installed 16 GW of new wind power capacity in 2010, bringing its accumulated installed capacity to 41.8 GW—thus making it the largest wind-installation country in the world [36]. Despite the rapid growth, the country's installed wind power capacity today is only a small part of its wind resource potential. One of main barriers to further development is the lack of transmission infrastructure.

4.4.3. Solar

Solar resources are receiving increasing attention in China. It is estimated that the annual surface absorption of solar energy is equivalent to approximately 1300 billion ton of standard coal equivalent (tce) [37]. Fig. 10 shows the distribution of the country's solar resources [37]. As can be seen, two-thirds of land area in China has abundant solar energy, particularly in the northwest, Tibet and Yunnan, with average annual radiation levels of over 6000 MJ/m^2.

The photovoltaic power generation is experiencing a rapid growth in China. In 2010, the country's annual production of photovoltaic cell was 8.7 GW, about half the world total. Meanwhile, China installed 500 MW of new photovoltaic capacity in 2010, bringing its accumulated installed capacity to 800 MW [38]. Previously, about half of installed capacity was used for supplying power to residents in remote rural areas and for special applications, such as communications and navigation [31]. Currently, the grid-connected photovoltaic power plant is receiving increasing financial support from Chinese government. The biggest photovoltaic power plant in China, 20 MW Xuzhou Xiexin Photovoltaic Power Plant, was successfully combined to the East China Power Grid at the end of 2009 [38].

4.4.4. Biomass

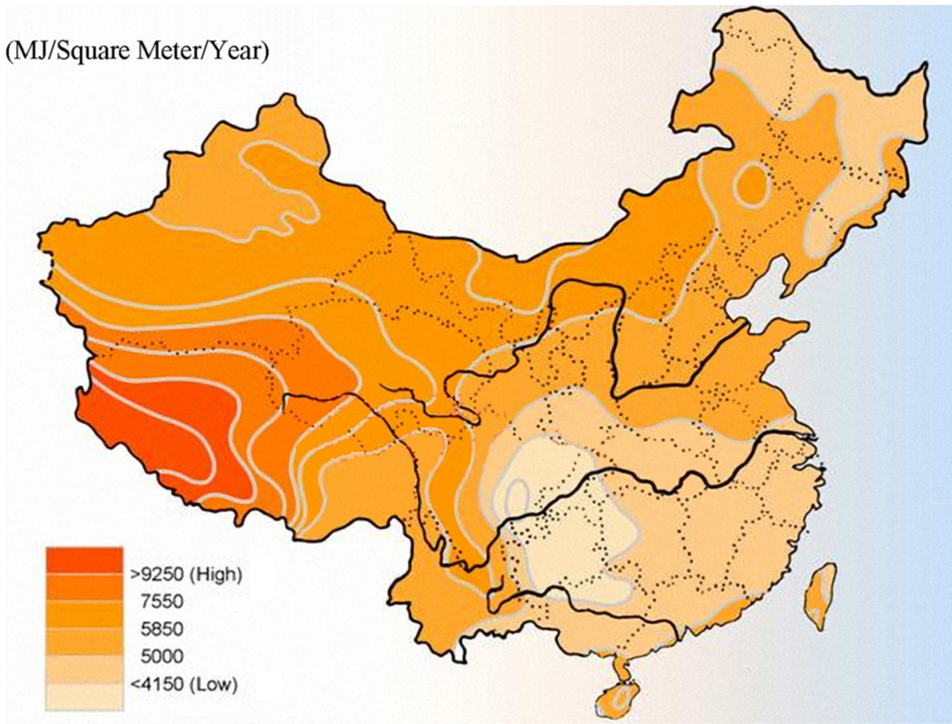
Biomass energy resources in China include straw and other agricultural wastes such as rice husks, waste from forestry and forest product processing, animal manure, energy crops and plantations, organic effluents from industry, municipal wastewater and municipal solid waste (MSW). Of about 600 Mt of crop straw produced every year, nearly 300 Mt (around 150 million tce) can be used as fuel. Around 900 Mt of waste from forestry and forest product processing is available each year, and nearly 300 Mt of this (about 200 million tce) can be used for energy production [32]. Presently, the nation's biomass resource that can potentially be converted into energy is about 500 million tce per year, less than 20% of current total primary energy consumption.

Biomass is utilized mainly through direct combustion for heating or cooking in China. In addition, biomass is wildly used for biogas generation, which provides clean cooking energy for the vast rural areas. At the end of 2005, the total number of household biogas digesters reached 18 million, with an estimated total annual production of 7 billion cubic meters. About 1500 large-scale biogas plants for livestock waste and organic industrial effluent produced a further 1 billion cubic meters [31]. Biogas is now widely integrated with animal husbandry and has become an important means of waste treatment in the agricultural sector. On the contrast, only a small proportion of biomass is used for power generation. By the end of 2005, the installed capacity of biomass power in China reached 2 GW. Bagasse (sugar cane residue) plants totaled 1.7 GW, while MSW incineration and land-fill gas power plants accounted for a further 200 MW; the remainder was agricultural or forestry waste gasification [31].

5. Research and development of hydrogen and fuel cell technology in China

5.1. Policy and programs

Project planning by Chinese government runs in a cycle of five year blocks, known as “five-year plans for the National Economic and Social Development of the People's Republic of China”. The Ministry of Science and Technology (MOST) sets the development targets and funding levels for various projects. Presently, the majority of hydrogen and fuel cell research in China is financially supported by MOST through two main programs: the National High Technology Research and Development Program (863 Program) and the National Basic Research Program (973 Program).



Source: Center for Wind and Solar Energy Resources Assessment, China Meteorological Administration

Fig. 10. Distribution of solar resources in China.

Table 2
Hydrogen and fuel cell projects supported by MOST through 973 and 863 Program.

Program	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
973	Large-scale production, storage and transportation of hydrogen and fuel cells										
973				Large-scale production of hydrogen using solar energy							
973						Highly efficient catalytic conversion of natural gas and syngas					
863		Post-fossil thematic program for hydrogen technology									
863		Post-fossil thematic program for high-temperature fuel cells									
863		Key program for electric vehicles									
863							Key program for energy-saving and new energy vehicles				
863								Key program for hydrogen production and high temperature polymer electrolyte fuel cells			
863							Annual thematic program for hydrogen and fuel cells				
863								Annual thematic program for hydrogen and fuel cells			

The previous five-year plans have all supported fuel cell and hydrogen technology to differing extents, due to the different overall aims of each plan [39]. In the 9th five-year plan (1996–2000), RMB 30 million ($4.75 million) was provided from the 973 Program and RMB 0.38 million ($60,143) from the 863 Program. The 10th five-year plan (2001–2005) saw an additional RMB 30 million ($4.75 million) invested, alongside RMB 22 million ($3.48 million) into generating hydrogen from solar power. Also during the 10th five-year plan MOST approved a RMB 880 million ($139 million) R&D program to develop advanced hydrogen technology, hybrid electric drives and fuel cell vehicles. In the 11th five-year plan (2006–2010), hydrogen and fuel cell technology research was awarded RMB 182.5 million ($28.88 million) out of a total advanced energy technology fund of RMB 634.3 million ($100.39 million). Funding totaling RMB 413 million ($65.37 million) was also provided for energy-saving and new energy vehicles, of which fuel cell vehicles were awarded RMB 150 million ($23.74 million). In 2011, 973 Program has $11.1 million of fuel cell funding available split equally into two projects: the first for solid oxide fuel cell (SOFC) research and the second for platinum-free fuel cells. Moreover, 863 Program has an additional $15.8 million available for hydrogen and fuel cell projects. Table 2 shows the hydrogen and fuel cell researches supported by 973 Program and 863 Program in recent years.

In addition to MOST, researchers can also obtain funding support from the National Natural Science Foundation of China (NSFC), which is a governmental organization directly affiliated with the State Council of China for the management of the National Natural Science Fund. As can been seen from Fig. 11, the number of hydrogen and fuel cell related projects supported by NSFC has been increasing steadily since 2000.

China also expresses great interest in participating international research cooperation through intergovernmental and non-

governmental channels. Among its global partners, the European Union is the most active one who has been involved in outstanding research cooperation with China. Under the Sixth and Seventh Framework Programme (FP6 & FP7) proposed by the European Commission, China participated in 8 projects in the field of hydrogen and fuel cell research, as listed in Table 3 [40].

5.2. Research and development

China starts its fuel cell research at Dalian Institute of Chemical Physics (DICP), Chinese Academy of Science (CAS) in the mid-1950s. Since then, DICP has been the leader of fuel cell research in China. Two types of alkaline fuel cell (AFC) were first developed for Chinese spacial program over the period of the 1960s and the 1970s, respectively. An alkaline free-electrolyte flow H_2–O_2 fuel cell and a large capacity oxidation–deoxidation electrolyte flow energy storage fuel cell were successfully developed in the 1980s. Consequently, the research and development of Proton Exchange Membrane Fuel Cell (PEMFC), Molten Carbonate Fuel Cell (MCFC), Solid Oxide Fuel Cell (SOFC), Direct Methanol Fuel Cell (DMFC) and Regenerative Hydrogen–Oxygen Fuel Cell (RFC) have been carrying out since the 1990. The series productions of PEMFC engines developed in DICP ranges from 30 kW to 100 kW. In 2001, DICP established Dalian Sunrise Power Co. Ltd. to facilitate the commercialization of fuel cells. In addition to DICP, other researchers have their own specialty: Shanghai Jiao Tong University sets up a 50 kW MCFC test system, while Shanghai Institute of Ceramics runs an 800 W SOFC test system. Both projects are supported by 863 Program.

As for fuel cells, Chinese interest in hydrogen began with the spacial program in 1960s, with the development of hydrogen as rocket propellant. Since then, many exciting developments have been reported in terms of hydrogen production and storage [41]. A novel biological hydrogen production process was developed in Harbin Institute of Technology. Through the process, hydrogen can be produced using organic waste water from starch manufacturers or food manufacturers via zymotechnics. In addition, it is not limited to immobilize high purity strains as required by conventional methods. The hydrogen production capacity reached 368 Nm^3/d in the test and the cost is about half of that of water electrolysis. High-performance magnesium-based composite material was invented with hydrogen storage capacity of 3.36 wt % at 150 °C. A pioneering manufacturing process of lanthanon alloy was designed with hydrogen storage capacity of 48 kgH_2/m^3.

On the other hand, the industry shows strong interest in the commercialization of hydrogen and fuel cell technology. Some of them have strong connection with local universities and institutes. Working with Bejing Ln-Power Sources Co., Ltd, Tsinghua University has successfully demonstrated various types of fuel cell vehicles since 1999. Shanghai Fuel Cell Vehicle Powertrain Co., Ltd has particularly strong links with Tongji University in developing "Chaoyue" series of fuel cell cars. DICP also works closely with its spin-off company Sunrise Power Co., Ltd. Close collaborations like these provide both a unique route to market for the researcher's technologies and at the same time offer the commercial enterprises access to state of the art research and technology. It is also worth mentioning that Beijing, Shanghai and Dalian have gradually become the main clusters of hydrogen and fuel cell researchers in China.

Intellectual property has attracted increasing attention of Chinese researchers. Table 4 summarizes international fuel cell patent applications and grants with China as priority country [39]. Looking back over the past ten years, no international activity was seen in 2000, with applications being logged in 2005 but none granted. In 2010, application activity continued and we began to see international patents being granted with China as the priority country. In terms of Chinese patents, although domestic companies are striving for more applications, foreign companies are still taking leading positions. Fig. 12 lists top 25 applicants for Chinese fuel cell patent during 1985–2010 [42]. As can be seen, none of top 3 applicants come from domestic researchers. The best records achieved by domestic researchers are 5th of Shanghai Shen-Li High Tech Co., Ltd and 7th of Dalian Sunrise Power Co., Ltd.

Chinese institutes, universities and companies who are involved in hydrogen and fuel cell R&D are summarized in Tables 5–7.

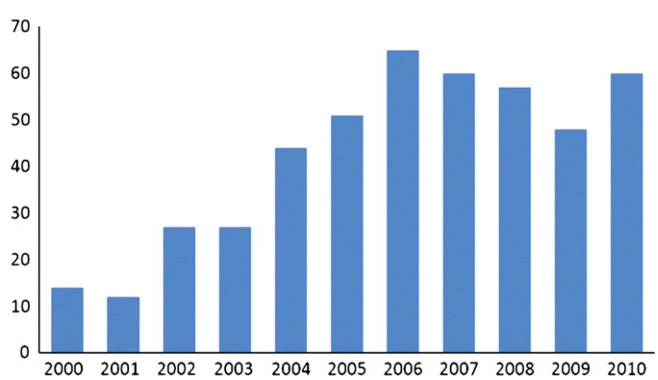


Fig. 11. Number of projects on hydrogen and fuel cell supported by NSFC.

Table 4
International patent applications and grants with China as priority country [39].

Year	Applications	Granted
2000	0	0
2005	21	0
2010	14	8

Table 3
Chinese participants in FP6 and FP7's hydrogen and fuel cell projects [40].

Title	Acronym	Chinese participants
New methods for superior integrated hydrogen generation system	NEMESIS	Nanjing Univ. of Tech
Carbon dioxide capture and hydrogen production from gaseous fuels	CACHET	Dalian Inst. of Chem. Phy, CAS.
International partnership for a hydrogen economy for generation of new ionomer membranes	IPHE-GENIE	Shanghai Jiao tong Univ.
Demonstration of SOFC stack technology for operation at 600 °C	SOFC600	Dalian Inst. of Chem. Phy, CAS. and Shanghai Jiao tong Univ.
Handbook for approval of hydrogen refueling stations	HYAPPROVAL	Tech. Inst. of Phy and Chem, CAS
Hydrogen for clean urban transport in Europe	HYFLEET: CUTE	China FCB Demonstration Project Management Office
Fuel cell testing, safety, quality assurance	FCTESQA	Dalian Inst. of Chem. Phy., CAS,
Carbon dioxide capture and hydrogen production with membranes	CACHET II	Dalian Inst. of Chem. Phy., CAS, and Inst. of Metal res., CAS.

5.3. Demonstration programs

5.3.1. Tianjin integrated gasification combined cycle power plant demonstration project

Due to its coal-based energy system, the clean utilization of coal has always been attached the highest priority in China. Motivated by this need, China launched its "Green Coal-Based Power Generation Plan". As the first part of the plan, Huaneng Group, the largest power company in China, started the construction of Tianjin integrated gasification combined cycle (IGCC) power plant in 2009. As one of the nation's 863 Program, the project has ambition to achieve near-zero emissions with the help of carbon capture and storage (CCS) technology. The first carbon storage site locates in Tianjin Dagang Oil Field. The first phase of the project has been completed by the end of 2011, including 2000 t/d coal gasifier and 250 MW coal-based poly-generation system.

5.3.2. Fuel cell bus demonstration program

The fuel cell bus demonstration project was launched by the Chinese government in March 2003 in collaboration with the Global Environmental Facility (GEF) and the United Nations Development Programme (UNDP). The first phase took place between June 2006 and October 2007, with three Daimler-Chrysler fuel cell buses in operation for use by the Beijing public. These buses traveled a total distance of more than 92,116 km during their service with average hydrogen consumption rate 1 kg/100 km. The second phase took place in Shanghai and was launched in November 2007. Three fuel cell buses trialed in the second phase were jointly developed by Shanghai Fuel Cell Vehicle Powertrain Co., Ltd and Tongji University, powered by Ballard stacks.

5.3.3. Bejing Olympics 2008

A total of 20 Passat fuel cell cars were operated during the 2008 Beijing Olympic Games, with total operation mileage over 76,000 km. These cars were designed by Shanghai Volkswagen Passat and co-manufactured by Shanghai Fuel Cell Vehicle Powertrain Co., Ltd, Tongji University and Shanghai Automotive Industry Corporation. After the Olympics, sixteen of them were sent to California for fleet demonstrations at the California Fuel Cell Partnership (CAFCP). Here, the fleet covered an additional 37,000 km between February and June 2009.

5.3.4. Shanghai World EXPO 2010

During the 2010 World Expo, a total of 1,017 clean energy vehicles were in use transporting visitors, including 90 fuel cell cars, 6 fuel cell buses. The fuel cell vehicles were manufactured by SAIC, Shanghai Volkswagen Automotive Co., Ltd, FAW-Volkswagen Automotive Co., Ltd, Chang'an Automobile Co. Ltd and Chery Automobile Co. Ltd. Hydrogen was brought to the Expo refueling station and the Anting hydrogen station on tube trailers from a by-product hydrogen purification plant; two mobile hydrogen refueling stations were also in use.

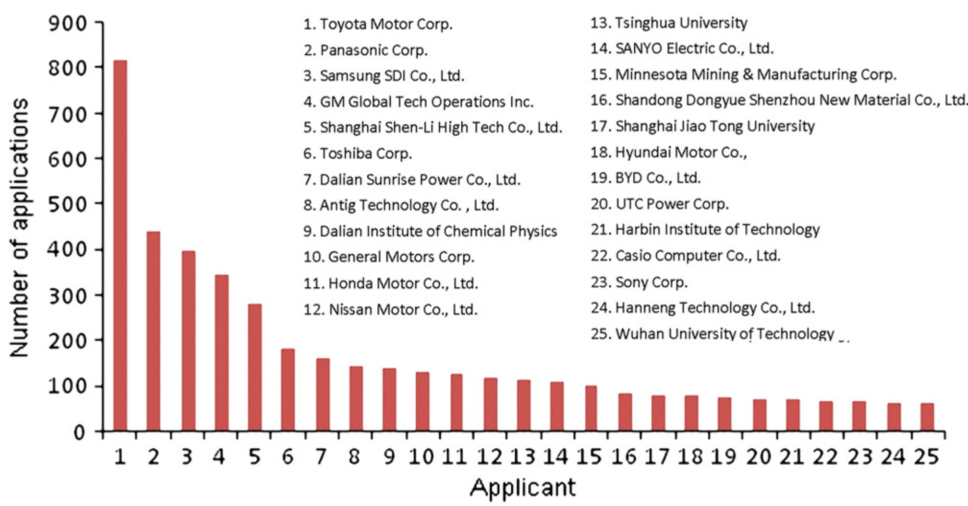


Fig. 12. Top 25 applicants for Chinese fuel cell patent during 1985–2010 [42].

Table 5
Summary of relevant Chinese institutes.

Institute	Research interests and progress	Selected reference
Dalian Institute of Chemical Physics (DICP)	DICP has broad research interests in fuel cells, including AFC, MCFC, SOFC, PEMFC, DMFC etc.	[43–47]
Changchun Institute of Applied Chemistry (CIAC)	CIAC has special interest in PEMFC, DMFC and MCFC. CIAC has been studying PEMFC since 1990s with emphasis on methanol reformer, catalyst and electrode manufacturing. CIAC also made great progress in studying intermetallic compound used for the anode and $LiAlO_2$ micro-powder used for the electrolyte of MCFC.	[48–50]
Guangzhou Institute of Energy Conversion (GIEC)	GIEC's research interests include microbio fuel cell (MFC) and hydrogen production.	[51,52]
Shanghai Institute of Ceramics (SIC)	SIC puts its emphasis on SOFC, specially the material used for electrode and electrolyte in SOFC. Excellent research has been done in processing ceramic and zirconia nano-powder used for the electrolyte.	[53–56]
Shanghai Institute of Organic Chemistry (SIOC)	SIOC focuses its research on key material and component in PEMFC, including proton exchange membrane, membrane electrode assembly and flow field plate.	[57]
General Research Institute for Nonferrous Metals (GRINM)	GRINM's research interest focuses on hydrogen storage techniques. Great progress has been made in studying metal hydride for hydrogen storage.	[58–61]

Table 6
Summary of relevant Chinese universities.

University	Research interests and progress	Selected reference
Tsinghua University	Tsinghua University's research interests include fuel cell engines and fuel cell buses, production, storage and transport of hydrogen.	[62–65]
Tongji University	Tongji University's research interests include fuel cell cars and hydrogen infrastructure. Tongji University successfully developed "Chaoyue" serious of fuel cell cars and established the first hydrogen fueling station in Shanghai.	[66–69]
University of Science and Technology of China (USTC)	USTC focuses its research on SOFC. Current research areas include mid-temperature SOFC, new material for electrode and electrolyte of SOFC.	[70–73]
Shanghai Jiao Tong University (SJTU)	SJTU's research interests include PEMFC, SOFC, and MCFC. Excellent research has been done in modeling and control of fuel cell systems.	[74–77]
Beijing Institute of Technology (BIT)	BIT's research interests include PEMFC, fuel cell vehicles, as well as hydrogen production and storage.	[78–81]
Tianjin University	Tianjin University has wide research interests, including SOFC, PEMFC as well as hydrogen production and storage.	[82–85]
Huazhong University of Science and Technology (HUST)	HUST's put its emphasis on SOFC. Current research areas include new material for electrode and electrolyte of SOFC, intermediate temperature SOFC.	[86–89]
South China University of Technology (SCUT)	SCUT's research interests include PEMFC, DMFC, SOFC, microbio fuel cell as well as hydrogen production and storage.	[90–95]
Wuhan University of Technology (WUT)	WUT puts its emphasis on PEMFC and fuel cell vehicles.	[96–99]
University of Science and Technology Beijing (USTB)	USTB has wide research interests in PEMFC.	[100–104]

Table 7
Summary of relevant Chinese companies.

Company	Research interests and products
Dalian Sunrise Power Co., Ltd	Established by DICP in 2001. Full spectrum of research from catalysts to fuel cell systems. Offers technical support and owns 200–300 fuel cell patents.
Shanghai Shen-Li High Tech Co., Ltd	PEMFC development and transport fuel cell demonstration are main focuses. Also has 10 kW hydrogen fueled stationary products and 100–300 W portable systems.
Shanghai Fuel Cell Vehicle Powertrain Co., Ltd	Focuses on research and development of fuel cell vehicles. Has close cooperation with Tongji University and Shanghai Automotive Industry Corporation (SAIC).
Shanghai Zhongke Tongli Chemical Material Co., Ltd.	Established by SIOC in 2002. Focuses on research of key material and components of PEMFC. Has fluorine-containing polymer membrane products.
Shanghai Everpower Power Technology Co., Ltd	Develops small PEMFC systems up to 5 kW for backup power and small vehicles. Staffs have 15–20 years fuel cell experience gained at fuel cell companies such as Ballard.
Pearl Hydrogen Technology Co., Ltd.	Focuses on commercialization of PEMFC for telecoms backup and light vehicles targeting greater lifetime and lower cost. Manufacturing capacity: 2 MW/year.
Shanghai Sunwise New Energy Systems Co., Ltd	Develops hydrogen refueling stations, including the permanent installation at Anting and a number of mobile units. Also develops on-board storage of hydrogen for FCEV.
Beijing Fuyuan Century Fuel Cell Power Co., Ltd	PEMFC development and commercialization. Has broad spectrum of products, ranging from fuel cells used in mobile phones to 40 kW fuel cell for vehicles.
Beijing Ln-Power Sources Co., Ltd	Current research areas are hydrogen production and PMEFC. Full spectrum of products, include hydrogen refueling station and various PEMFC system.

6. Conclusions

In this work, we reviewed key issues associated with future hydrogen economy in China, including drivers for the transition towards the hydrogen economy, energy resources and their potential role in hydrogen production, government's policy and support for the research of hydrogen related technologies.

Among the four drivers identified, energy security seems to be the most important one for China. Need for alternative fuel is especially urgent in the transport sector. The growing oil price in China, as well as the tightening financial belts caused by the economy crisis, has evoked widespread public's interests in renewable energy vehicles. In 2010, Chinese government established the renewable energy vehicle union, which consisted of 16 state-owned powerful companies. The objective of the union is to facilitate the research and commercialization of renewable energy vehicles. With strong government incentives, renewable energy vehicles are likely to expand their market share in near future. As a result, the dependence on oil import can be greatly alleviated by then.

The brief analysis of energy supply shows that China currently faces a dilemma in terms of hydrogen production. The country's coal-based energy system is both beneficial and detrimental to the transition towards hydrogen-based economy. In favor of hydrogen economy is the availability of so much potential hydrogen fuel, while the current reliance on coal, the low price of "dirty" energy delivery and the established infrastructure of the coal power industry may make it difficult to increase industrial momentum towards the hydrogen economy. On the other hand, the oil and natural gas are not the ideal sources for hydrogen production due to their high price and limited reserve. In the long term, renewable energy resources are likely to play a more important role in hydrogen production due to their abundance in China. The major barrier to the commercialization of renewable energy is the high cost of infrastructures, which results in the expensive electricity tariff and the low market acceptance. Under such circumstances, government incentive is an effective way to encourage renewable energy production.

Chinese government has made ambitious policy and provides strong financial support for hydrogen and related technology

development. All the top-tier universities and institutes in China are conducting hydrogen and fuel cell research. Of the various fuel cell types, the high temperature variants—SOFC and MCFC—are most suitable for hydrogen that is derived from hydrocarbon sources. Unlike low temperature cells such as the PEMFC, both the SOFC and MCFC can tolerate carbon oxides in the fuel and indeed are able to oxidize CO directly. Studies have shown that fuel produced from coal gasifiers can be used in the SOFC and MCFC. Considering the country's coal-based energy system, this may be an important application in the future.

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